



# SmallSat Navigation via the Deep Space Network: Lunar Transport

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Mission Design & Navigation  
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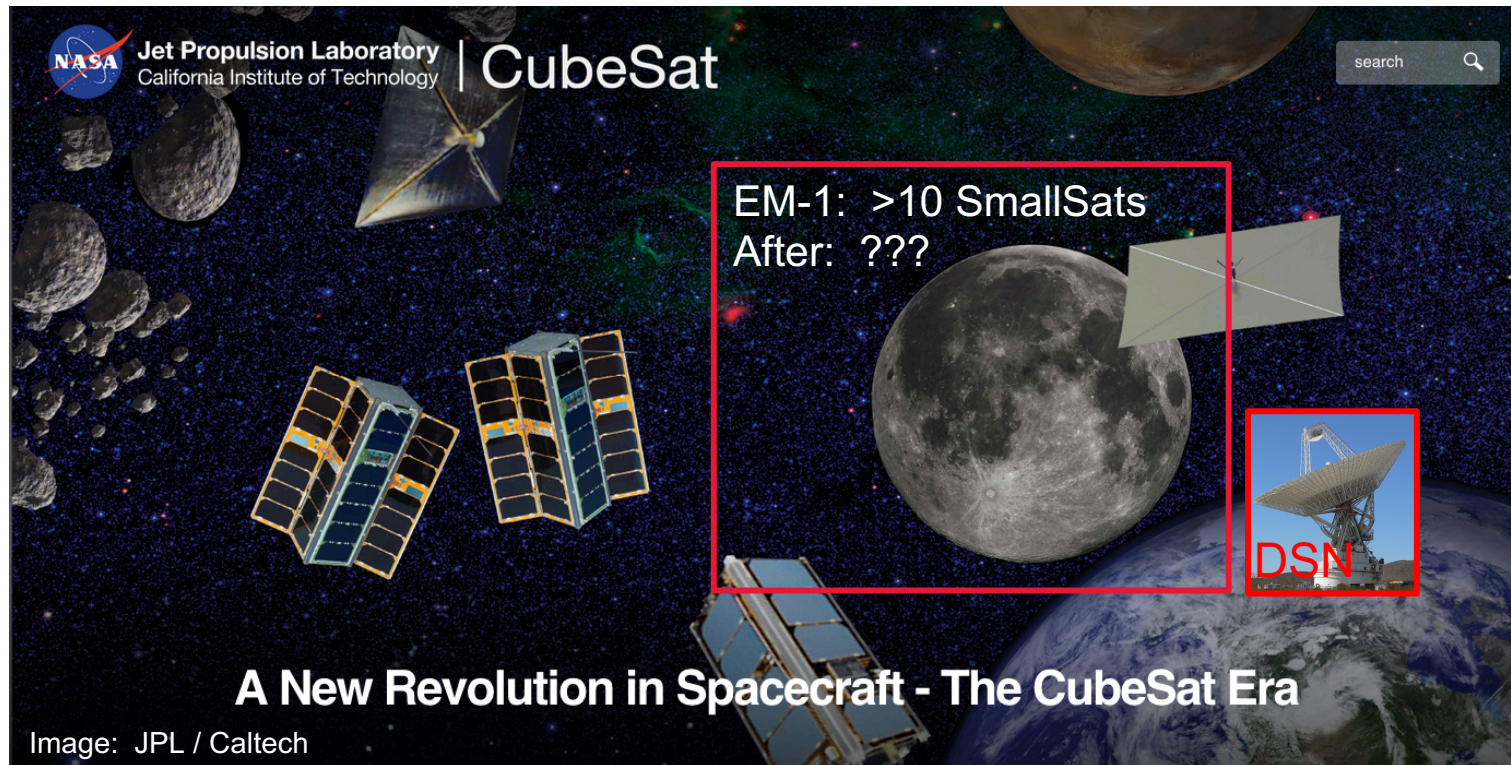


**Jet Propulsion Laboratory**  
California Institute of Technology



# The CubeSat Revolution

<https://www.jpl.nasa.gov/cubesat/info.php>



# A Catalogue of DSN Support Options

## Radiometric Tracking & Orbit Determination Performance

- Rough order-of-magnitude estimates
- DSN Measurement Types
  - Two-way Doppler & ranging
    - Line-of-sight
    - “Gold standard”
  - DDOR / VLBI
    - Plane-of-sky
    - Commonly added
  - One-way Doppler & ranging
    - Line-of-sight
    - CSAC enabled (SA.45S - Symmetricom)
    - Multiple Spacecraft Per Aperture (MSPA)
    - On-board clock modeling required

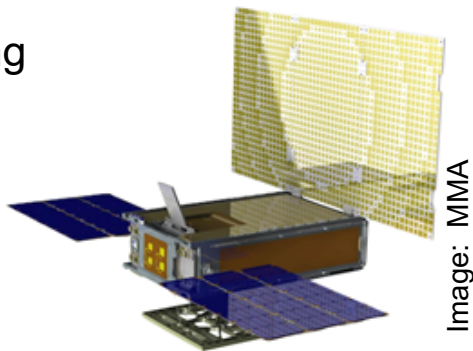


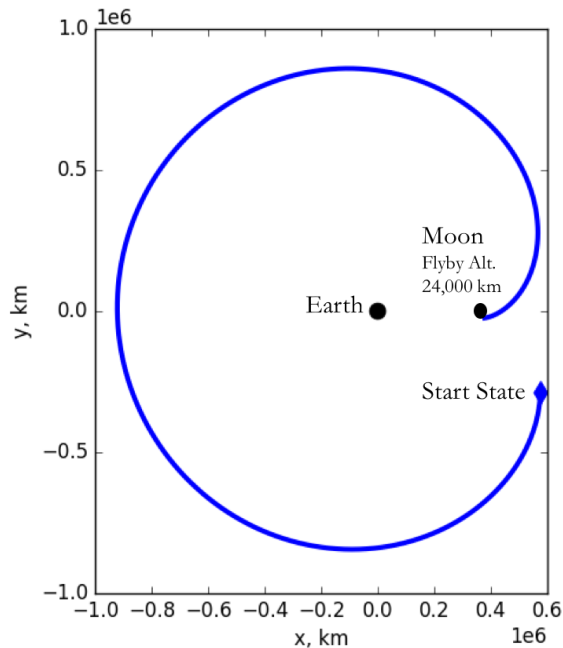
Image: MMA



Image: JPL / Caltech

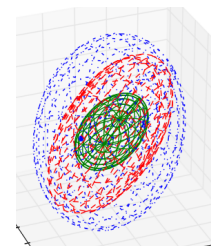
# Reference Mission Scenario

## Approach to lunar flyby



Earth-Moon Synodic Frame

Parameter	Value	Units
X-band frequency	7.9e9	Hz
Two-way Doppler noise	5.62e-3	Hz
Two-way SRA noise	1.0	m
One-way Doppler noise	8.17e-2	Hz
One-way range noise	5.0	m
CSAC white noise (1-day)	2.15e-3	Hz
CSAC random walk (1-day)	6.44e-2	Hz
CSAC Allan deviation (1-day)	4e-11	s/s
DDOR noise	0.06	ns



# Sample Tabular Results

## 2-way Doppler Only

### Position Uncertainty - **Reconstruction** @ Data Cut-Off

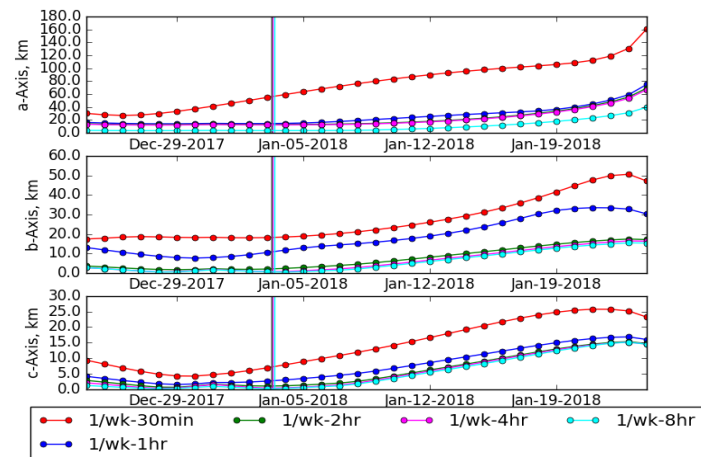
Passes / Week	Pass Duration				
	30 min.	1 hr.	2 hrs.	4 hrs.	8 hrs.
1	(54.93, 18.1, 6.89)	(14.58, 10.43, 2.6)	(13.09, 1.91, 1.02)	(12.43, 0.57, 0.36)	(3.67, 0.47, 0.09)
2	(37.85, 7.06, 4.02)	(7.91, 3.6, 1.66)	(1.81, 1.05, 0.57)	(0.41, 0.34, 0.27)	(0.27, 0.23, 0.08)
3	(7.22, 4.06, 1.19)	(4.77, 1.89, 1.01)	(1.41, 0.82, 0.43)	(0.35, 0.27, 0.22)	(0.22, 0.19, 0.05)
7	(2.56, 2.07, 0.72)	(2.18, 1.08, 0.59)	(0.93, 0.58, 0.31)	(0.28, 0.21, 0.19)	(0.17, 0.12, 0.05)

### Position Uncertainty - **Prediction** @ Flyby / Close Approach

Passes Per Week	Pass Duration				
	30 min.	1 hr.	2 hrs.	4 hrs.	8 hrs.
1	(160.8, 47.3, 23.2)	(75.0, 30.3, 16.0)	(69.4, 17.1, 14.7)	(66.8, 16.2, 14.5)	(39.8, 15.3, 14.5)
2	(91.9, 25.1, 17.9)	(41.0, 20.9, 15.0)	(35.7, 15.4, 14.0)	(35.4, 14.9, 13.7)	(35.4, 14.9, 13.7)
3	(36.7, 17.2, 16.1)	(36.2, 16.5, 14.6)	(35.5, 15.2, 13.9)	(35.4, 14.9, 13.7)	(35.4, 14.9, 13.7)
7	(21.6, 13.8, 11.0)	(21.4, 13.2, 10.9)	(20.5, 11.4, 10.7)	(17.1, 10.0, 9.3)	(15.2, 9.1, 8.6)

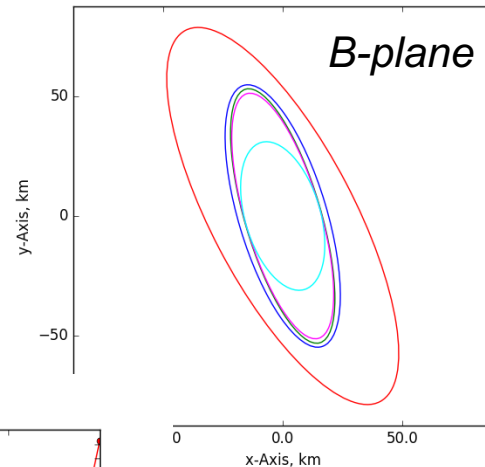
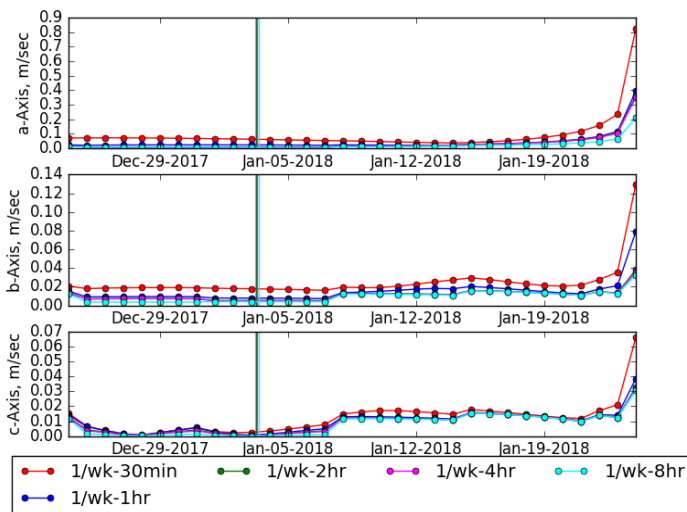
# Sample Image Results

2-way Doppler only, 1 pass / week



*Position Uncertainty*

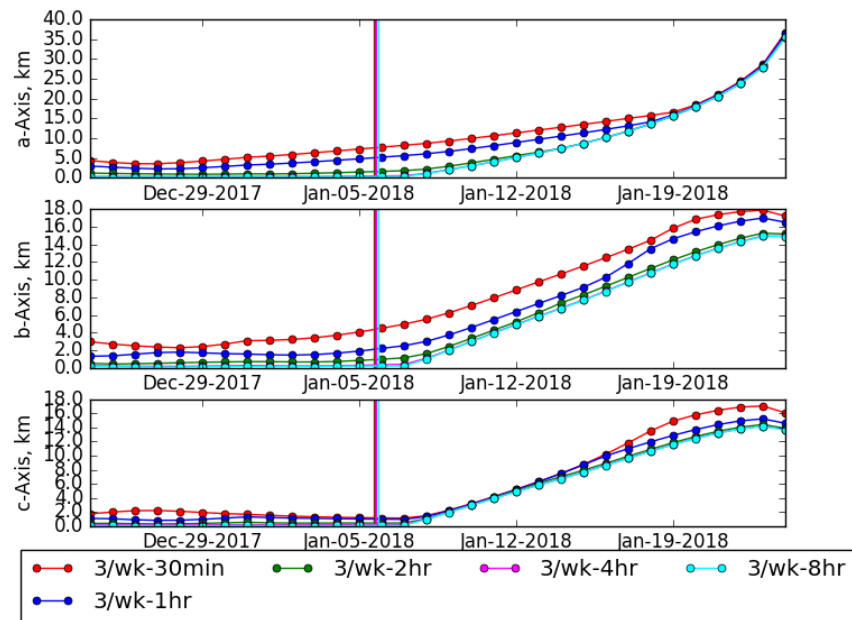
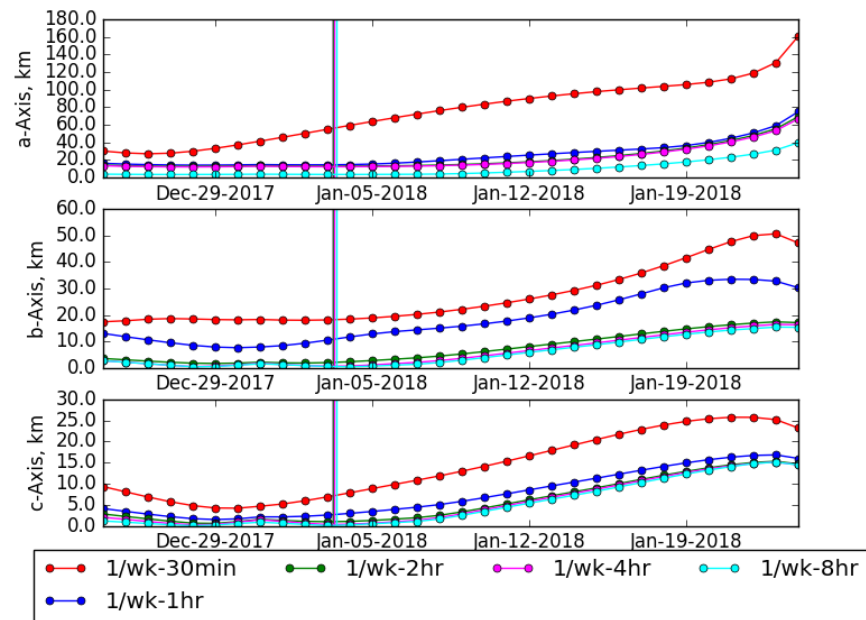
*Velocity Uncertainty*





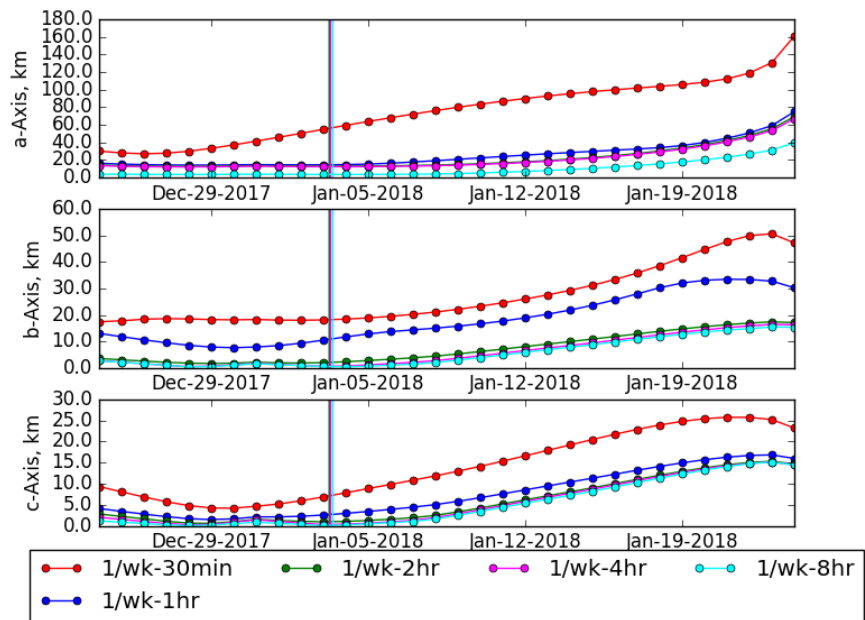
# Pass Frequency

## 2-way Doppler only

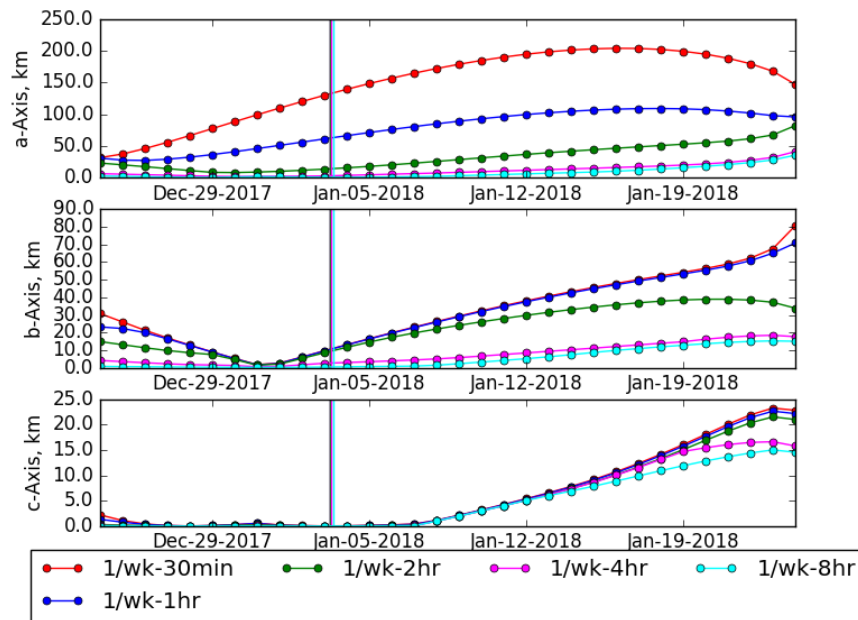


# Doppler vs Range

2-way, 1 pass / week



*Doppler Only*

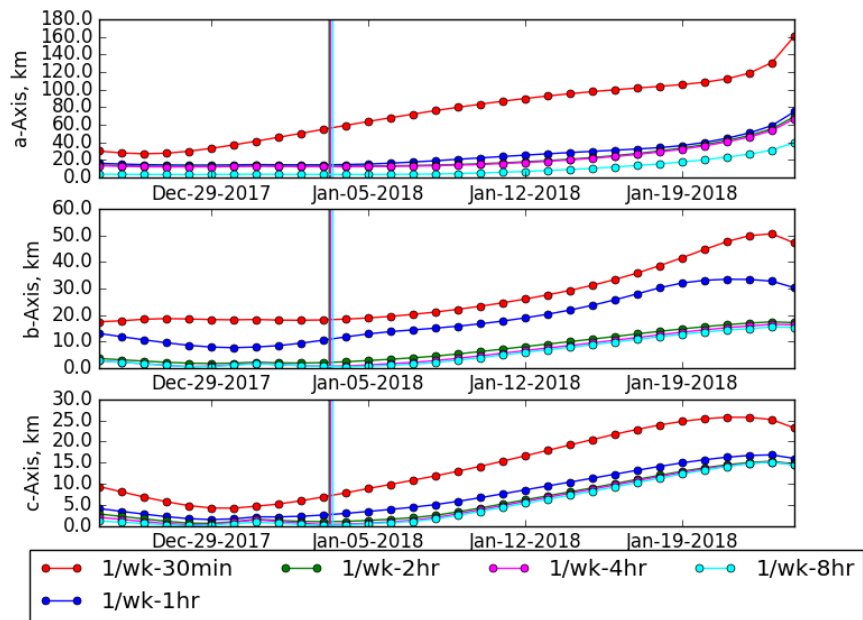


*Range Only*

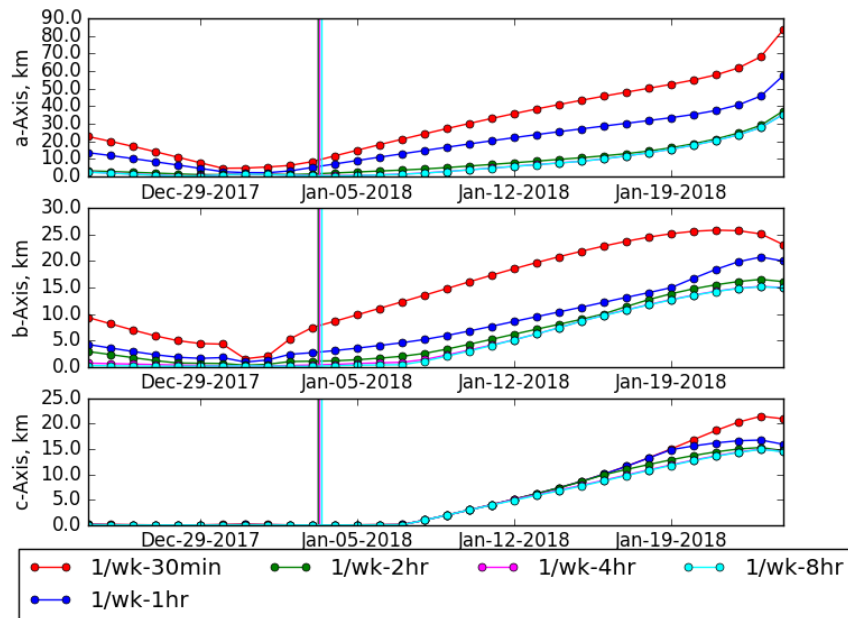


# Doppler + Range

2-way, 1 pass / week



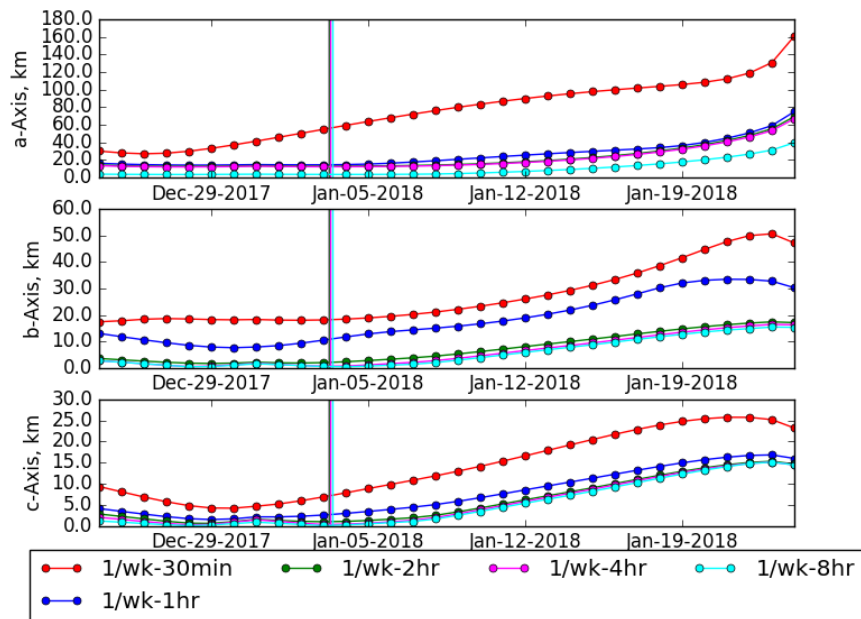
*Doppler Only*



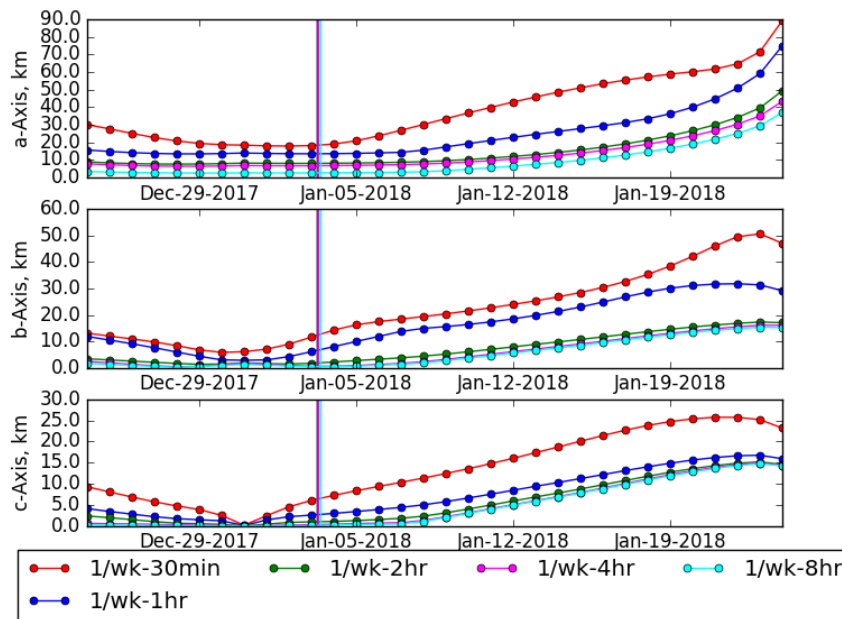
*Doppler + Range*

# Doppler + DDOR

1 pass / week



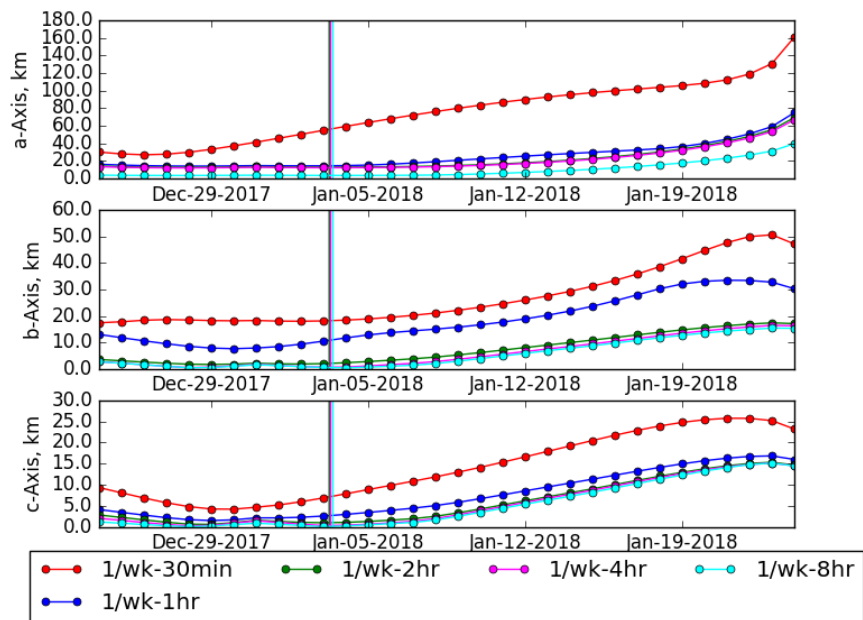
*Doppler Only*



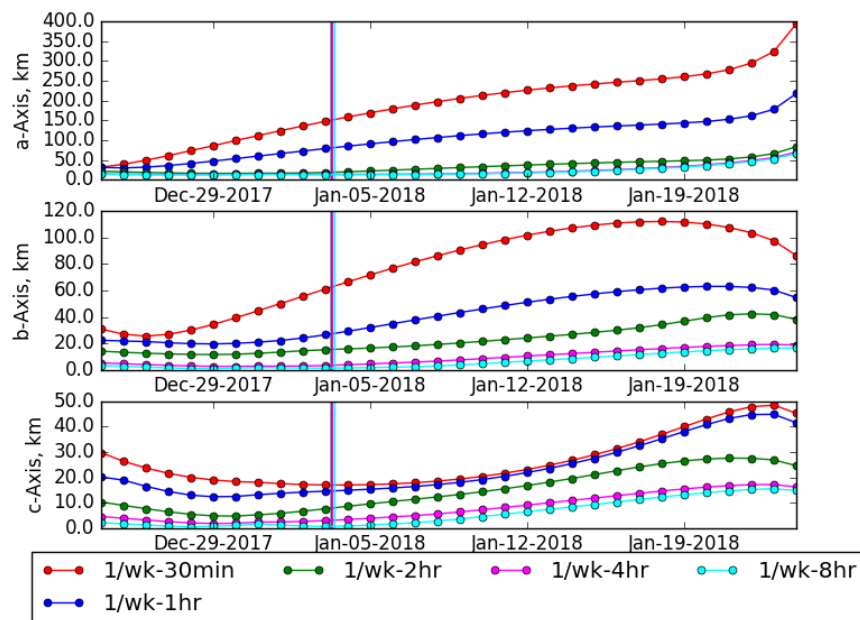
*Doppler + DDOR*

# Doppler 2- vs 1-way

1 pass / week



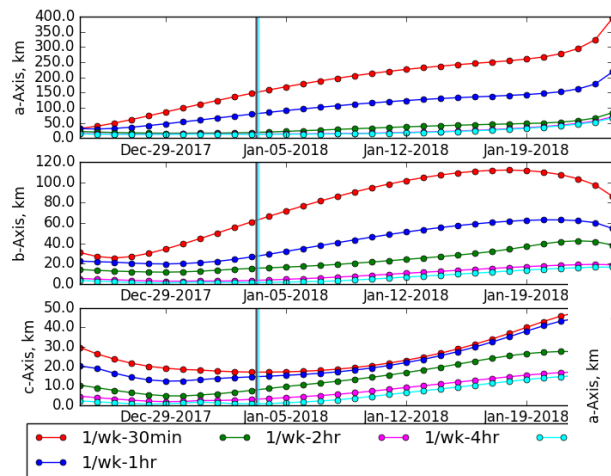
2-way



1-way

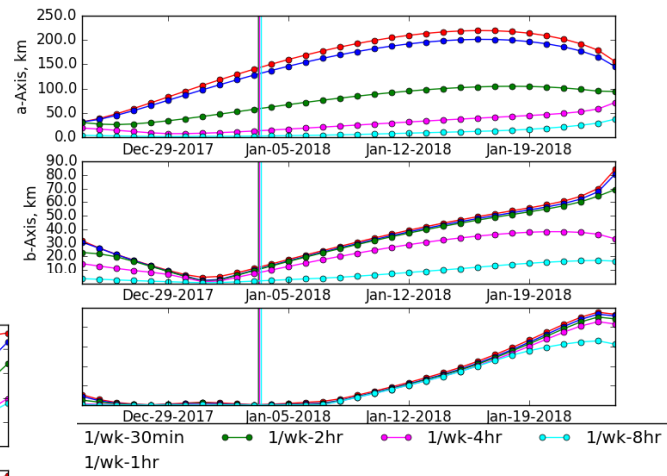
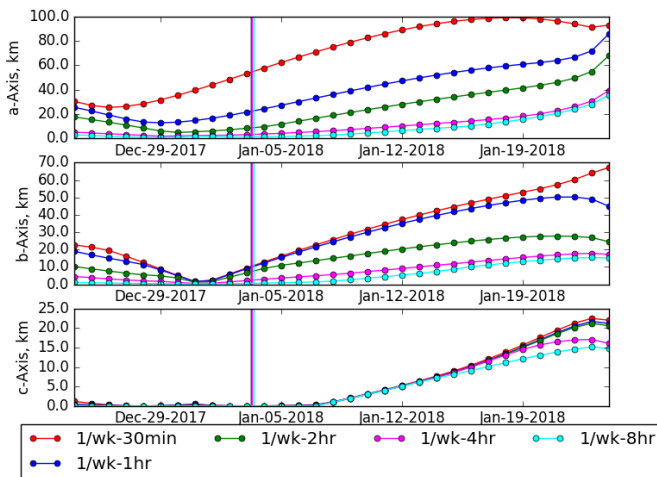
# 1-way Radiometric Tracking

1 pass / week



*Doppler only*

*Doppler + Range*



*Range only*



# Summary

## Observations & Recommendations

- Uncertainties vary by data type, tracking schedule
  - Reconstruction:  $150 \text{ km} \Rightarrow 20 \text{ m}$ ,  $15 \text{ cm/s} \Rightarrow 0.2 \text{ mm/s}$
  - Prediction @ flyby:  $400 \text{ km} \Rightarrow 15 \text{ km}$ ,  $2 \text{ m/s} \Rightarrow 9 \text{ cm/s}$
- Many possible combinations to give similar state knowledge
  - Longer tracking passes > more frequent passes
  - Doppler + range > Doppler + DDOR
- 2-way > 1-way, as is expected
  - Opportunistic MSPA increases 1-way availability
  - Requires use of CSAC or similarly precise timing system
- NOTE: Results only valid for lunar transport scenario
  - Could be extrapolated to lunar orbits, with correct assumptions

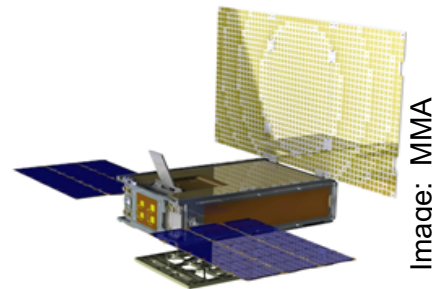


Image: MMA



Image: JPL / Caltech



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